TECHNICAL REPORT
70-45-ES

WEATHER EXTREMES AROUND THE WORLD

by
Pauline Riordan

January 1970

UNITED STATES ARMY
NATICK LABORATORIES

Earth Sciences Laboratory
ES-53

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Geography Division

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FOREWORD

In 1955 a map titled "World Weather Extremes" was prepared by the Cartography Branch of the Environmental Protection Research Division, Quartermaster Research and Engineering Center, for distribution to visitors and other interested persons. This map showed the location of certain meteorological extremes which had been recorded in climatological publications. In subsequent years the map was periodically revised as new records came to light and the number of requests for it increased. It has been reprinted in a number of publications, both military and civilian, and has been widely used for instruction and display purposes.

During the past year a new need for the map appeared in the Earth Sciences Laboratory at Natick, requiring updating of the map and a review of the validity of the records depicted. This was in connection with a revision of Military Standard 210A, "Climatic Extremes for Military Equipment," for certain portions of which Natick Laboratories has been assigned responsibility. As an indication of the most extreme climatic conditions that have been recorded in various parts of the earth, the map gives an approximation of the absolute limits within which design criteria must be established.

In preparing the present revision of the map of world weather extremes and a new map showing extremes in North America, the sources for all records shown were reviewed and documented. When controversial records were included, the arguments for and against their acceptance were examined and summarized in the text. For many of the records, the text includes such information as the conditions responsible for occurrence of the extremes, problems of measuring or recording them, and the kinds of investigations carried out by the US Weather Bureau before accepting them. Thus for the first time a map of extreme weather occurrences is presented together with full documentation of the sources of the records and references to pertinent comments in the technical literature.

Valuable advice and information was received from Mr. M. A. Arkin, Chief of the Foreign Branch, Environmental Data Service, ESSA, whose assistance is acknowledged with appreciation.

The cartography in this report was completed by Miss Kristin Gill and Miss Olive Lesueur, under the direction of Aubrey Greenwald, Jr. Chief of the Cartography office, Earth Sciences Laboratory.

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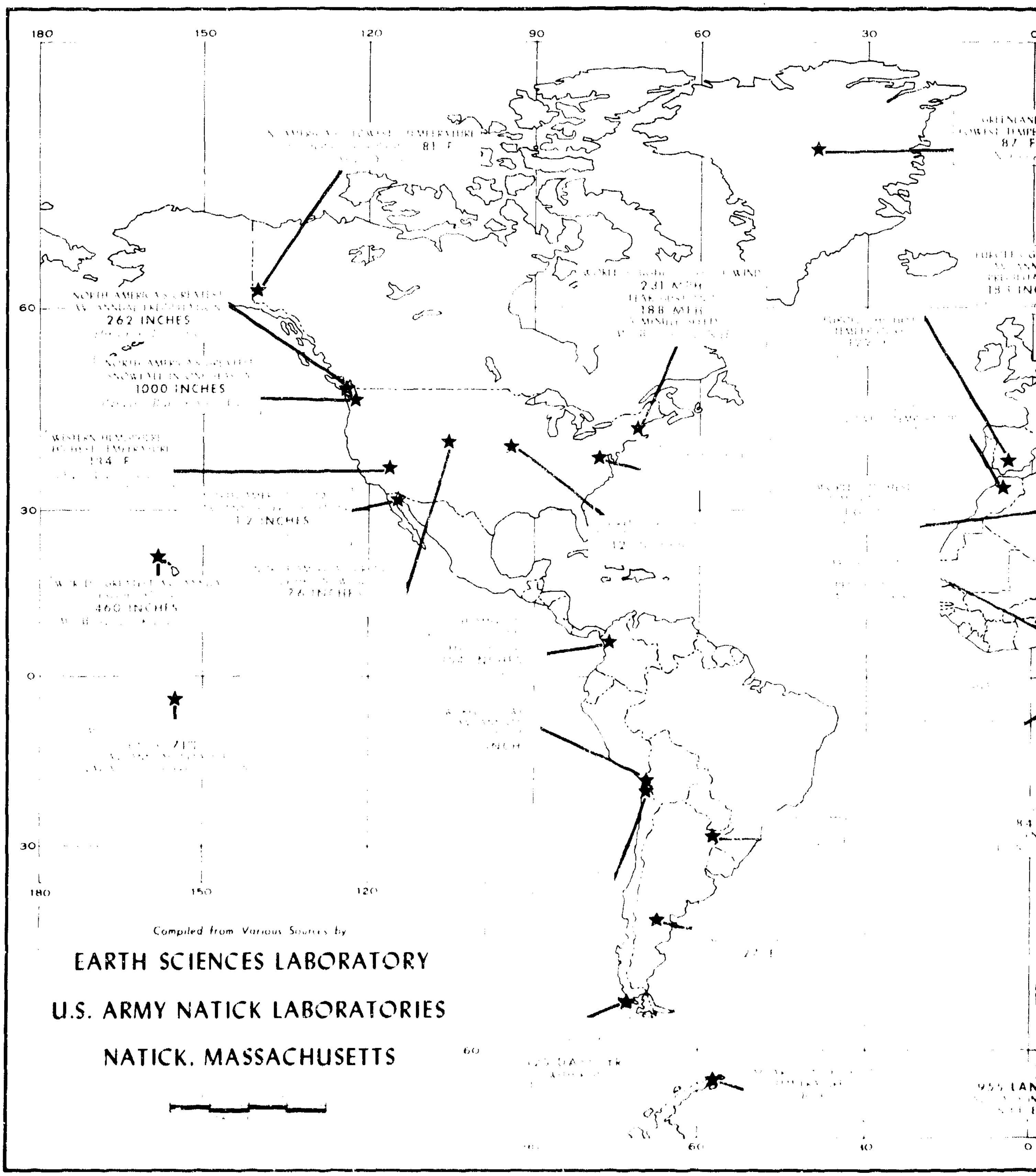
ABSTRACT

This report consists of a map of world and continental weather extremes and a map of North American weather extremes, with comments on the reliability of the records shown. Included are highest and lowest temperatures, largest temperature ranges, greatest and least amounts of precipitation for various durations, maximum precipitation variability, greatest thunderstorm frequency, highest and lowest atmospheric pressure, highest solar radiation, largest hailstones, greatest snowfall, highest wind speed, highest humidity, and most frequent occurrence of dense fog. Both the absolute extreme and the most extreme annual average are given for most of the elements. As far as possible, the records are taken from official sources, and all of them are documented. Conditions of site, instrumentation, observational procedure, and other factors pertinent to the reliability of extremes are discussed.

WEATHER EXTREMES



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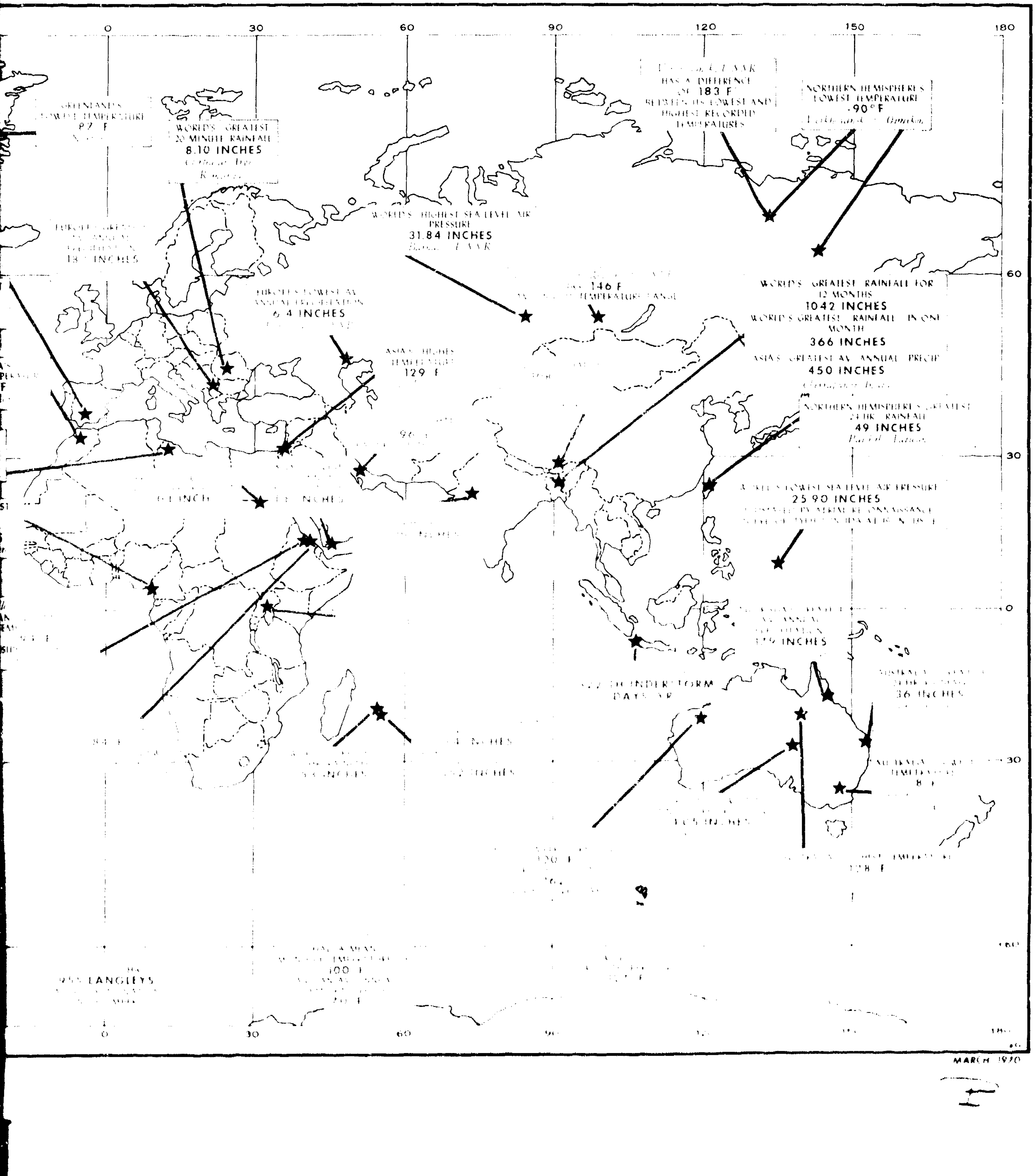
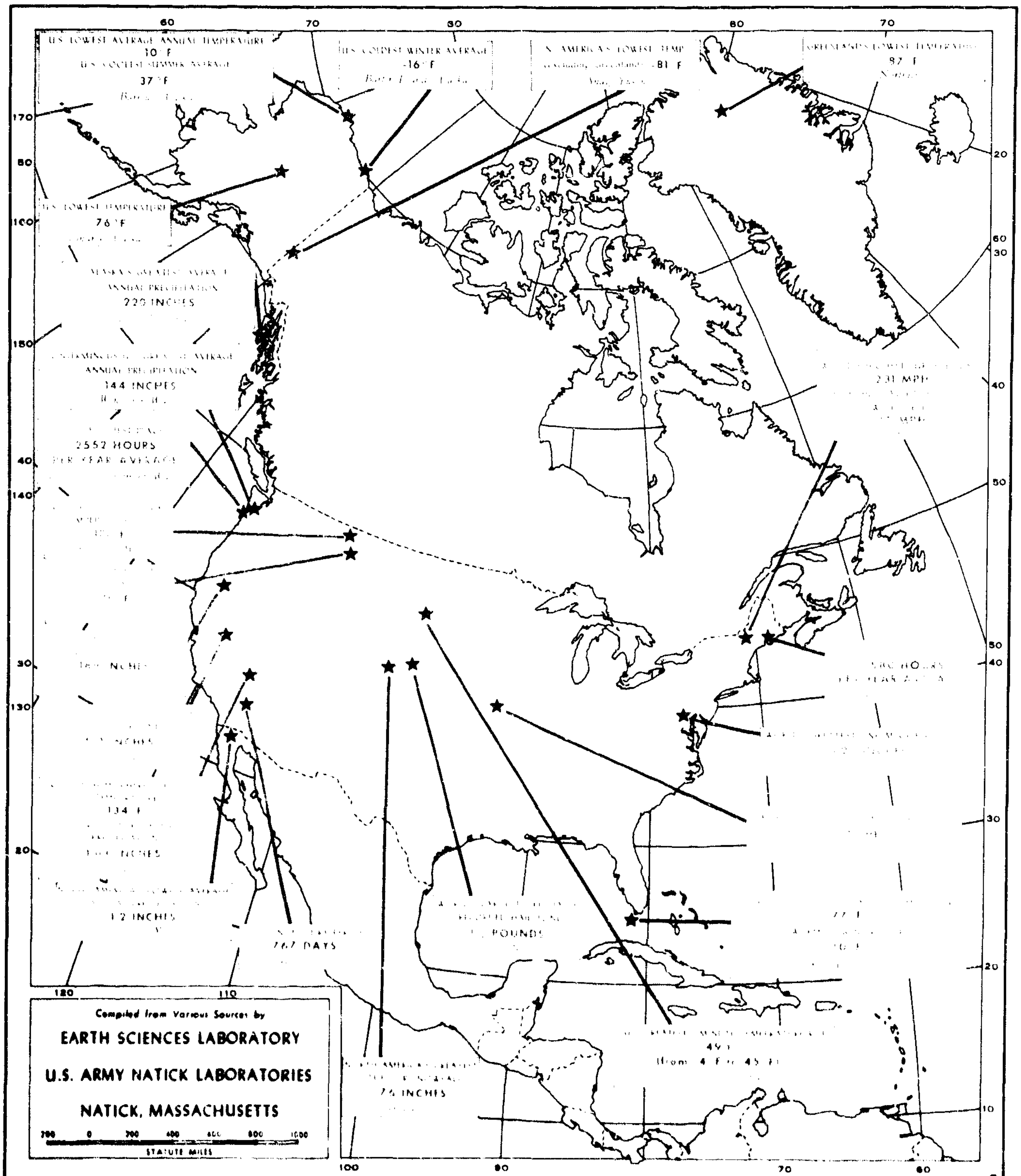
EMES AROUND THE WORLD



MARCH 1970

WEATHER EXTREMES IN NORTH AMERICA



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WEATHER EXTREMES AROUND THE WORLD

1. Introduction

The revised world map (Fig. 1) and the new map of North America (Fig. 2) were prepared primarily as aids in revising a Military Standard specifying extreme climatic conditions for design of military equipment. The two maps together include some 78 records. In selecting them the categories of extremes indicated in MIL-STD 210A were kept in mind, but selection was not limited to these categories. This report is intended, primarily, to review the validity of the records. A listing of them, with documentation of their sources, is followed by a commentary on their reliability.

The representativeness and significance of weather records, in general, are commented upon, and for each of the main elements, certain factors bearing on reliability are noted. Among these are measuring instruments and problems, environmental conditions which tend to cause extremes, theoretical limits of occurrence, and the geographical areas and seasons in which the probability of extremes is greatest. Following this general treatment, pertinent information about individual records and their documentation is given. There is much information available about some of the extremes, especially controversial ones, but little or nothing about others. Similarly, records are more easily available for the United States than for other countries. For this reason, and because many Americans would be especially interested in records of their own country, the North America map has been added.

In addition to documenting each of the records, we have coordinated them, where possible, with determinations of the Environmental Data Service, part of the U. S. Environmental Science Services Administration. In the United States, EDS is responsible for archiving and disseminating weather data, and in line with these functions it determines extreme occurrences, both at home and abroad, which might be of interest to the public (1). Other countries follow a similar policy, but there is, as yet, no world agency that determines and establishes a register of weather extremes. As a result, a given record might be accepted by EDS but not by its equivalent agency in some other country.

2. Weather Extremes Included on the Maps

To facilitate finding the extremes for a particular element, the records are listed, with documentation, by elements. Each list is arranged in order of decreasing severity of the values shown, starting with the world's record if known. Those which are included only on the North America map are indicated by an asterisk (*), and a few records that are not shown on either map are indicated by a double asterisk (**). Values are rounded off to the nearest whole degree.

a. TEMPERATURE

(1) Highest Temperature

	Reference[a]
World, 136°F, El Azizia, Libya, 13 Sep 1922	2
Western Hemisphere, 134°F, Death Valley, Calif., 10 Jul 1913	2
Asia, 129°F, Tirat Tsvi, Israel, 21 Jun 1942	3
Australia, 128°F, Cloncurry, Queensland, 16 Jan 1889	4
Europe, 122°F, Seville, Spain, 4 Aug 1881	3
South America, 120°F, Rivadavia, Argentina, 11 Dec 1905	3
Antarctica, 58°F, Esperanza, Antarctic Peninsula, 20 Oct 1956	3
Persian Gulf had a 96°F sea surface, 5 Aug 1924	2
Dallol, Ethiopia, has a 94°F average annual (possibly the world's highest)	5
U.S. highest average annual, 77°F, Key West, Florida*	6
U.S. warmest winters, 70°F average, Key West, Florida*	2
Western Hemisphere hottest summers, 98°F average, Death Valley, California**	2
Marble Bar, West Australia, had temperatures of 100°F or above on 162 consecutive days, 30 Oct 1923 to 7 Apr 1924	4

(2) Lowest Temperature

World, -127°F, Vostok, Antarctica, 24 Aug 1960	2
Northern Hemisphere, -90°F, Verkhoyansk, U.S.S.R., 5 and 7 Feb 1892; and Oimekon, U.S.S.R., 6 Feb 1933	2
Greenland, -87°F, Northice, 9 Jan 1954	2
North America, excluding Greenland, -81°F, Snag, Yukon, 3 Feb 1947	2
U.S., -76°F, Tanana, Alaska, Jan 1886*	2
U.S., excluding Alaska, -70°F, Rogers Pass, Mont., 20 Jan 1954*	2
South America, -27°F, Sarmiento, Argentina, 1 Jun 1907	3
Africa, -11°F, Ifrane, Morocco, 11 Feb 1935	3
Australia, -8°F, Charlotte Pass, New South Wales, 14 Jun 1945 and 22 Jul 1947	4
Plateau Station, Antarctica, had a mean monthly of -100°F, Jul 1968, and an average annual of -70°F, 1966-68	7
U.S. lowest average annual, 10°F, Barrow, Alaska*	2
U.S. coolest summers, 37°F average, Barrow, Alaska*	2
U.S. coldest winters, -16°F average, Barter Island, Alaska*	2

* On North America map only
** Not mapped
a See references at the end of this report

(3) Greatest Range of Temperature

	Reference
Verkhoyansk, U.S.S.R., has a difference of 183 F° (-89.7°F to 93.5°F) between its lowest and highest recorded temperatures	8
Eastern Sayan Region of U.S.S.R. has 146 F° (93.2°F to -53.2°F) average annual temperature range	8
U.S. greatest 2-minute temperature rise, 49 F° from -4° to 45°F, Spearfish, South Dakota, 22 Jan 1943*	9
U.S. greatest 24-hour temperature fall, 100 F° from 44°F to -56°F, Browning, Montana, 23-24 Jan 1916*	2
Rapid City, South Dakota, had 3 temperature rises and 2 falls of 40 F° or over during a period of 3 hours, 10 minutes, 22 Jan 1943**	9

b. PRECIPITATION

(1) Greatest Rainfall

World, one-minute, 1.23 inches, Unionville, Md., 4 Jul 1956	10
World, 20-minute, 8.10 inches, Curtea-de-Arges, Romania, 7 Jul 1889	10
World, 42-minute, 12 inches, Holt, Mo., 22 Jun 1947	10
World, 12-hour, 53 inches, Belouve, La Réunion I., 28-29 Feb 1964	10
World, 24-hour, 74 inches, Cilaos, La Réunion I., 15-16 Mar 1952	10
Northern Hemisphere, 24-hour, 49 inches, Paishih, Taiwan, 10-11 Sep 1963	10
Dharampuri, India, had a 24-hour rainfall of 39 inches, 2 Jul 1941 - possibly the world's greatest on flat terrain	12
Australia, 24-hour, 36 inches, Crohamhurst, Queensland, 3 Feb 1893	13
World, 5-day, 152 inches, Cilaos, La Réunion I., 13-18 Mar 1952	10
World, one-month, 366 inches, Cherrapunji, India, Jul 1861	10
World, 12-months, 1042 inches, Cherrapunji, India, Aug 1860 to Jul 1861	10

(2) Greatest Average Annual Precipitation

World, 460 inches during a 30-year period, Mt. Waialeale, Kauai, Hawaii	14
Asia, 450 inches during a 74-year period, Cherrapunji, India	3
Africa, 405 inches during a 32-year period, Debundscha, Cameroon	3
South America, 354 inches during a 10-16 year period, Quibdo, Colombia	3
North America, 262 inches during a 14-year period, Henderson Lake, British Columbia	3
Alaska, 220 inches, Little Port Walter*	6
Europe, 183 inches during a 22-year period, Crkvice, Yugoslavia	3
Australia, 179 inches during a 31-year period, Tully, Queensland	3
U.S., conterminous, 144 inches, Wynoochee, Washington*	6
Bahia Felix, Chile, has an average of 325 days/year with rain	15

(3) Least Precipitation	Reference
Iquique, Chile, had no rain for 14 consecutive years	11
U.S. longest dry period, 767 days, Bagdad, California, 3 Oct 1912 to 8 Nov 1914*	15

(4) Lowest Average Annual Precipitation

World, .03 inch during a 59-year period, Arica, Chile	6
Africa, <0.1 inch during a 39-year period, Wadi Halfa, Sudan	3
North America, 1.2 inches during a 14-year period, Bataques, Mexico	3
U.S., 1.63 inches, Death Valley, California*	6
Asia, 1.8 inches during a 50-year period, Aden	3
Australia, 4.05 inches during a 34-year period, Mulka, South Australia	3
Europe, 6.4 inches during a 25-year period, Astrakhan, U.S.S.R.	3

(5) Variability of Precipitation

Debundscha, Cameroon, has 75 inches average annual variability**	16
Malden Island, Line Islands, has a 71% average annual relative variability	16
Lhasa, Tibet, had a 108% average annual relative variability, 1935-38	17

(6) Hailstones

Largest officially recorded hailstone, 1-1/2 pounds, Potter, Neb., 6 Jul 1928*	15

(7) Greatest Snowfall

North America, 24-hour, 76 inches, Silver Lake, Colo., 14-15 Apr 1921	11
North America, one storm, 189 inches, Mt. Shasta Ski Bowl, California, 13-19 Feb 1959*	11
North America, one season, 1000 inches, Paradise Ranger Station, Washington, 1955-56	11
U.S. greatest depth of snow on the ground, 451 inches, Tamarack, California, 11 Mar 1911*	11

c. OTHER ELEMENTS

(1) Thunderstorms

Kampala, Uganda, has 242 average annual thunderstorm days	18
Bogor, Indonesia, had 322 average annual thunderstorm days, 1916-19	19

(2) Sea-Level Air Pressure

	Reference
World's highest, 31.84 inches, Barnaul, U.S.S.R., 23 Jan 1900	6
World's lowest, 25.90 inches, estimated by aerial reconnaissance in the eye of Typhoon Ida at 19°N, 135°E, 24 Sep 1958	11

(3) Solar Radiation

South Pole has 955 langleys, average daily insolation in December	20

(4) Wind Speed

World's highest peak gust, 231 miles per hour, Mt. Washington, New Hampshire, 12 Apr 1934	21
World's highest 5 minutes, 188 miles per hour, Mt. Washington, New Hampshire, 12 Apr 1934	11
U.S. highest average annual, 35 miles per hour, Mt. Washington, New Hampshire*	6

(5) Dew Point (Humidity)

Assab, Ethiopia has 84°F average afternoon dew point in June	22

(6) Fog Frequency

U.S. highest average annual, 2552 hours, Cape Disappointment, Wash.	6
Eastern U.S. highest average annual, 1580 hours, Moose Peak, Maine	6

3. Commentary on Reliability of the Records

What makes a record acceptable, and if so, to whom? To insure comparability of meteorological observations, various regulations concerning site, instrumentation, and procedure have been established by the World Meteorological Organization (23). Observations taken in accordance with these regulations, over which some sort of quality control is exercised to correct observational errors that might appear, would be accepted by the national meteorological agencies (1). Also, for extreme average conditions, the period of observations should be long enough to be representative. However, even after records have been accepted by appropriate agencies their reliability is still sometimes questioned.

When an extreme phenomenon is observed and recorded in conformance with prescribed procedures, and the record is accepted by the appropriate meteorological service, what does that record represent and indicate? It represents the most extreme acceptable record that is available and indicates that the particular value is possible because it has been observed. It does not necessarily--or even probably--mean that it is the highest value that could occur or ever has occurred. According to M. A. Arkin,

"record extremes must be taken with a grain of salt" (1). He explains that news of an extreme weather occurrence is not always widely disseminated, meteorological records are relatively short, stations are very few, and "even the densest network of stations provides only a very small sample of the weather". To this it can be added that records may be established which the observers do not recognize as records, and sometimes suspected records are not verified because of difficulties in validating.

a. Temperature

Air temperatures are measured at standard heights varying in different countries from 4 to 6 feet above ground level. The values obtained can be affected by radiation from the sun, sky, earth, and other surrounding objects, and precautions need to be taken to protect the measuring instruments from radiation. Also, adequate ventilation must be provided to insure representation of the circulating air. In addition to these requirements concerning height, radiation protection, and ventilation, there are requirements pertinent to construction and accuracy (manufacturing tolerance) of the measuring instruments.

Highest and lowest temperatures are recorded at more than 10,000 weather stations throughout the world (24). Maximum and minimum thermometers which stay at the highest or lowest point, respectively, reached during the reading period (generally 12 hours) are used to record them. Maximum thermometers are generally of the mercury-in-glass type. But since mercury freezes below about -32°F, minimum thermometers contain other liquids such as ethyl alcohol; these are commonly called spirit thermometers because of the type of liquids used.

(1) High Temperatures

Factors contributing to outstandingly high temperatures have been listed by the British meteorologist, H. H. Lamb (25). These factors are as follows:

"(i) Strong heating of the surface, most effective on dry desert sand or bare rock, when the sun is high and when the atmosphere is especially clear.

(ii) Long sojourn or long passage of the air over the warmest surface available.

(iii) Subsidence, which inhibits both vertical convection and local circulations, such as sea breezes, that have a three-dimensional development.

(iv) Föhn effect or passage of the air stream over mountains, most effective when condensation and rainfall produced during ascent result in latent heat of condensation being stirred into the air. (The word "stirred" is appropriate because the air parcels receiving the liberated heat must be dispersed through many layers of the atmosphere in the overturning which occurs after the crest is passed.) Föhn effect also helps to intensify the insolation received at places to the leeward, because rainfall during ascent washes suspended impurities out of the air, thereby tending to produce ideal transparency of the atmosphere after crossing the mountains.

(v) Advection from regions where the air has already been heated."

Lamb's investigations suggest that conjunction of all of these influences might occur during record high extremes, and that very many of the peak temperatures "are associated with the speeding up, and longer fetch, of warm air advection just ahead of a cold front". Further, he concludes that these extreme high temperatures "may have been very local and associated with some locally forced turbulence--for instance, in air descending some sort of declivity or merely passing over town buildings--the circumstances being such as to raise adiabatically by a degree or two the temperature of already very warm air at a slightly higher level" (25).

The highest possible temperature that could occur has been considered by the German meteorologist, Hoffmann (24). According to him, because warm air is lighter, air near the hot ground surface seeks to rise above overlying layers which are cooler. Thus, an ascending air stream is established through which the hot air escapes so that the temperature of the lower air levels should not rise above a theoretically definable value. He puts this value at slightly over 55°C (131°F) and states that world weather observations confirm it. The highest accepted record is 58°C (136°F), at El Azizia in North Africa, but several claims have been made of higher temperatures. The highest was 167°F in the Gobi Desert of interior Asia (4). Possibly some of these claims are valid, but most of them were obtained with thermometers which were not correctly exposed in the shade and had been affected by radiation from hot sand.

Most extreme high temperatures have been recorded near the fringes of the deserts of North Africa and southwestern United States, in shallow depressions where rocks or sand reflect the sun's heat from all sides. In the Sahara, greatest extremes are recorded toward the leeward coast, after the air has passed over the heated desert.

Besides the highest temperatures, the world's highest average temperatures are also of interest. These include the highest average annual, seasonal, monthly, and daily temperatures, also the highest average--in

contrast to absolute--maxima for these periods. For example, highest temperatures of the year average 122°F or above in some parts of the world: the northern and western Sahara; Death Valley, California; low-lying desert areas in Iran; and a small part of western Pakistan (24). By contrast, some parts of Antarctica such as the South Pole, Vostok, Sovietskaya, and Plateau Station have average annual maxima below 0°F.*

World's highest temperature:
136°F
El Azizia, Libya, 13 Sep 1922

El Azizia is located in the northern Sahara at 32°32' N, 13°01' E, elevation 367 feet (26). At least 30 years of observations are available for the station (26), and the climate has been described by Eredia (27). Besides the 58°C (136.4°F) reported in September 1922, maximum temperatures of 133°F and 127°F for August and June, respectively, are listed for El Azizia (26).

This record (58°C) is "generally accepted as the World's highest temperature recorded under standard conditions" (2, 15), but it has been questioned. A. Fántoli, who was Director of the Libyan Meteorological Service at the time the observation was reported, has written about the subject (28, 29), and summaries in English are available (30, 31). Although he was unable to investigate personally the reliability of the reading at the time it occurred, he has since then examined the evidence in some detail: the exposure; effect of instrument shelter or of instrumental error; records for pressure, wind, and humidity at three other stations in Tripoli for 9-12 September 1922; and synoptic charts for the area for 10-14 September 1922. He also reviewed temperature records at El Azizia for June to October 1914-1922, as well as the maximum temperatures (99° to 118°F) at 10 places in Tripoli on 11-14 September 1922. From his investigations, Fántoli concluded that although there was an unusually violent and persistent ghibli** at the time, the probable or tentative maximum on 13 September 1922 was 56°C (132.8°F).

Fántoli's conclusion may have been influenced, in part, by the comparatively low maximum temperatures at nearly stations, a point also mentioned by other authors (33). Lamb's theories on the restricted locales of peak temperatures (24) might be an answer to this, but to form an opinion, we would need to know more about the local conditions such as topography. Lamb also investigated the El Azizia record, and from his investigations has described the synoptic situation which caused the extreme

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*Personal communication, T.O. Frostman, Regional Environments Division, Earth Sciences Laboratory, U.S. Army Natick Laboratories, Natick, Mass.

**A ghibli is a hot, dust-bearing wind in Tripolitania (32).

heat (25). A cold front was advancing eastward from Algeria and advection of warm air from the Saharan interior was established some distance ahead of the front. Tripoli had strong southerly winds for two sucessive days before the front passed. Rainfall in mountains to the south in the Auderas area (17° N, 8° E) contributed latent heat of condensation to the winds.

Western Hemisphere's highest temperature:
134°F
Death Valley, Calif., 10 Jul 1913

Death Valley, at 37° N, 117° W, is a desert below sea level, flanked by mountains. It has the hottest summers in the Western Hemisphere (2). The temperature of 134°F, recorded at Greenland Ranch Station, is accepted by the U.S. Weather Bureau as an official record. If Fántoli and others are correct in their estimate of 133°F for the maximum at El Azizia, then Death Valley could hold the world's record for high temperature. However, as Lamb says, "Authenticity has been officially accepted in this (Death Valley) and the Azizia case only after some discussion, but there is no doubt that both were extreme days" (25). He describes the synoptic situation as follows: "On July 10, 1913, a cold occlusion was passing east across the Rockies in 35°-50° N. There was anticyclonic curvature in the air streams on both sides of the front and clear skies, probably with subsidence, over the deserts. It was blowing very hard ... the hot wind must inevitably have had its temperature further raised by adiabatic compression in the abrupt descent from the surrounding highlands". A. Court (34) has examined the Death Valley record in detail: the surrounding environment, the equipment and procedures used for taking the observation, weather conditions at the time it occurred, and temperature frequencies at the station over a period of record from 1911 through 1947. During this period a maximum temperature of 127°F was reached or exceeded on eight days in July 1913, the year of the record, but it was reached in only two other years (35). However, during the later period from 1948 to 1967, a maximum of 129°F was recorded (35). From his analysis of the 1911-1947 data, Court determined that a temperature of 134°F has an expectancy of only once in 650 years (34). He concluded that "constantly increasing accuracy in weather observations and higher standards of instrument exposure make it seem probable that no future official observation will exceed the present high temperature record for North America now held by Death Valley" (34).

Persian Gulf had a sea-surface temperature of
96°F
5 Aug 1924

This sea surface temperature, measured by the SS Frankenfels, is "among the highest recorded" (2). However, sea temperature in the Persian Gulf has been known to reach 98°F in August and September (36). Although the 96°F record is not an absolute maximum in the sense of being the highest known, it was suggested for inclusion here to indicate how hot the

sea surface can become. The Persian Gulf also has very high average temperatures in summer, 88°F during July and August (2).

Dallol, Ethiopia, has an average annual temperature of 94°F, possibly the world's highest

Highest average daily and annual temperatures occur at lower latitudes than do the absolute extreme high temperatures. The highest averages occur in places which are hot in summer and remain warm in winter; in such places, the daily minima are very high also. These places are found at low elevations, away from coasts, and within the latitude belt between 12° and 20° N across Africa and possibly the southwestern Arabian peninsula (5). Within this zone, annual mean daily maxima of 102°F are recorded at Abecher, Chad (6 years), and of 101°F at Merowe, Sudan (30 years) and Araoune, Mali (8 years). These values are the highest listed in the British Meteorological Office Tables of Temperature, Relative Humidity and Precipitation for the World (26).

Dallol is situated at 14°19' N, 40°11' E, at an altitude of 258 feet below sea level. It is on the edge of the Danakil Depression, a salt desert. By averaging Dallol's annual mean daily maximum temperature of 106°F (a possible world record) and its annual mean daily minimum of 83°F (another possible world record), an annual mean temperature of 94°F is obtained (5). This value could be a new record, exceeding the 88°F of Lugh Ferrandi, Somalia, which has been cited as probably the world's highest average annual temperature (2). The Lugh Ferrandi average is for the years 1923 to 1935.

The Dallol temperatures were obtained from readings taken at a climatological station maintained at the base camp of an American prospecting company over a period of six years, 1960-1966. Maximum and minimum temperatures were recorded "using standard thermometers kept at a height of four feet in a ventilated screen" (5). Although the period of observation is short, comparison of the results with 20-year means at a nearby location (Khormaksar) indicates that the values should not differ greatly over a long-term period (5).

D. E. Pedgley has considered areas whose annual mean daily maxima might equal or exceed Dallol's (5). According to him, in the lowest part of the Danakil Depression, which reaches a minimum of about 390 feet below sea level some 20 miles south of Dallol, the annual mean daily maximum might be a "fraction of a degree Fahrenheit greater" than at Dallol (5). Also, in the Abecher area, where there is a "descent of potentially warmer air resulting from a blocking by the Marra Mountains of the north-easterlies that blow for much of the year" there might be low-lying places with values similar to Dallol's.

(2) Low Temperatures

Extreme low temperatures result from "the simultaneous occurrence of an optimum combination of several meteorological elements, absence of solar radiation, clear skies, and calm air are the most essential requirements, with the ultimate fall in temperature dependent upon the duration of these conditions" (37). During such conditions, there is minimum mixing of the vertical air layers. As the ground surface loses heat through terrestrial radiation, the nearest air layers become cooled and, consequently, heavier than the layers above them. Therefore there is no possibility of their rising and allowing the cold air to escape as the warm air does. Since this process continues as long as the conditions remain favorable, there can be a greater buildup of cold than of heat. Thus, the lowest temperatures, to -127°F, fall farther below the standard atmosphere's temperature of 59°F (38) than the highest temperatures, to 136°F, rise above it.

Extremely cold temperatures occur in interior high-latitude localities with clear skies, conducive to maximum terrestrial radiation, and with topographic features which afford protection from wind. Geographic areas of extreme cold are the eastern Antarctic plateau (approximately 9,000 to 12,000 feet in elevation); the central part of the Greenland Icecap (approximately 8,200 to 9,800 feet in elevation); Siberia between 63° and 68° N and between 93° and 160° E (below 2,500 feet in elevation); and the Yukon basin of northwestern Canada and Alaska (below 2,500 feet in elevation).

Average annual minimum temperatures can range from around 80°F in places like Dallol, Ethiopia, to a possible -130°F in the Antarctic. This difference of about 210 F degrees between the highest and lowest minima is considerably greater than the difference of about 125 F degrees between the highest and lowest maximum temperatures. Some values for the world's coldest areas are -76°F in Siberia, below -85°F on the Greenland Icecap, and from about -94° to -130°F in the Antarctic (24). The -130°F value is considered possible as an average annual minimum, even though -127°F is the lowest temperature recorded, because only Vostok, Sovietskaya, and Plateau Station have taken temperature measurements for short periods in the extensive cold area of East Antarctica, and presumably none are at the cold pole of Antarctica.

World's lowest temperature:
-127°F
Vostok, Antarctica, 24 Aug 1960

The theoretical minimum temperature that could be reached has been calculated by Shliakhov (39) and by McCormick (37). Shliakhov estimated -80° ± 2°C at about four kilometers altitude (i.e., -112°F at about 13,123 ft) with a decrease of 0.5°C for every further 100 meters rise in height. This estimate was exceeded when the temperature fell to -87.4°C (-125°F) at Vostok, Antarctica (78°27' S, 106°52' E, elevation 11,220 ft)

in 1958 and again, in 1960, when the world record low temperature of -126.9°F occurred, also at Vostok. The basic error in Shliakhov's calculations, according to H. Wexler (40) resulted from associating a zero radiation balance with a certain temperature--the theoretical minimum. McCormick has calculated the possible minimum that could occur during "virtually optimum conditions ... assumed to persist during the polar night (about 180 days)" (37). The resultant value, -200°C (-328°F) is "hardly realistic for the troposphere" where, apparently, wintertime radiative energy losses are compensated by advective gains. However, it might be more applicable to the ozonosphere where such "energy-balancing processes are not equally operative" (37).

Northern Hemisphere's lowest temperature:
-90°F
Verkhoyansk, U.S.S.R., 5 and 7 Feb 1892 and
Oimekon, U.S.S.R., 6 Feb 1933

Very low winter temperatures occur in the Verkhoyansk-Oimekon cold zone, approximately between 63° and 68° N, and 93° and 160° E. It is an area of extreme continentality, lying near the eastern end of the world's largest land mass and blocked off by mountain ranges from the moderating influence of oceans. Air pressure is high, and there is considerable radiational cooling because winter nights are long at such latitudes. A value of -89.7°F was recorded at Verkhoyansk (67°34' N, 133°51' E, elevation about 350 feet) in 1892, and -89.9°F was recorded at Oimekon (63°28' N, 142°49' E, elevation about 2,165 feet) in 1933. Of the two places, Oimekon is potentially the colder, being located at a higher elevation and more closed in by mountains. It is possible that the temperature there may have fallen below the value recorded; temperatures of -95°F and down to -108°F have been claimed (41, 16, 42). Considerable controversy has arisen about the Verkhoyansk records due to problems concerning instrument corrections, and about both the Verkhoyansk and Oimekon records because of misleading references to incorrect values in the literature (7, 43, 44).

Greenland's lowest temperature:
-87°F
Northice, 9 Jan 1954

On the permanent icecap, which covers most of the interior of Greenland, temperatures are very low due both to loss of heat through radiation and to evaporative cooling from the snow and ice surface (45). A temperature of -86.8°F has been recorded at Northice (78°04' N, 38°29' W, elevation 7,687 feet), a station established by the British North Greenland Expedition (46). Since the period of record for Northice was only 20 months (November 1952 - June 1954) and temperatures below -75°F occurred 16 times, it is quite probable that temperatures there have been lower than -87°F at other times (47). Also, temperatures of -87°F have been reported from two other places on the icecap: at an elevation of 9,820 feet on 6 December 1949, and at a French expedition station (location not identified) on 22 February 1950 (11).

North America's lowest temperature (excluding Greenland):
-81°F
Snag, Yukon 3 Feb 1947

Snag is located near the Alaskan border of Canada's Yukon Territory, at 62°23' N, 140°23' W, elevation 2,120 feet. The lowest gradation on the minimum thermometer which recorded this extreme was -80°F, but a pencil mark was made at a distance about four degrees below -80 (48). However, subsequent laboratory calibration of the thermometer indicated an instrumental error of +3 degrees; and a value of -81.4°F was officially set by the Canadian Meteorological Service (48, 41, 49). On the preceding day, 2 February, the corrected minimum temperature was -80.1°F (49). The previous record Canadian low temperature was -78.5°F at Fort Good Hope in the Northwest Territories, on 30 December 1910 (41).

U. S. lowest temperature:
-76°F
Tanana, Alaska January 1886

Tanana is located at 65°10' N, 152°06' W, elevation 220 feet, in the Yukon Valley in central interior Alaska. Although the record is accepted by the U. S. Weather Bureau, the particular day in January 1886 on which it occurred is not cited in WB publications (2, 11). Lower temperatures than -76°F are also claimed for Alaska. A temperature of -78°F was recorded by an airways observer at Fort Yukon (66°34' N, 145°18' W, elevation 417 feet) on January 14, 1934, two days after the weather station closed there--which made the record unofficial (15). A minimum thermometer left at 15,000 feet on Mt. McKinley for 19 years indicated a temperature lower than -100°F at some time during its exposure (15).

Plateau Station, Antarctica, had a mean monthly temperature of
-100°F
July 1968
and an average annual temperature of -70°F, 1966-68

Plateau Station is located at 79°15' S, 40°30' E, elevation 11,890 feet. It is in or near the coldest part of the Antarctic, which is believed to be close to the ridge line in East Antarctica (50). At Plateau Station, the July mean temperature for 1968 is believed to be a new world record, -99.8°F*. During the winter of 1968, there were 118 days with temperatures below -100°F**. A Russian station, Sovietskaya, at 78°24' S, 87°35' E, elevation 11,713 feet, reported an average annual temperature of

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*Personal communication, P. Dalrymple, Chief, Regional Environments Division, Earth Sciences Laboratory, U.S. Army Natick Laboratories.

**U.S. Army Natick Laboratories. Annual Record of Major Events - FY 1969. Natick, Mass., 1969.

-71°F during the IGY period in 1957-1958 (41). This is colder than Plateau Station's -70°F, but the area is not considered to be as cold. The periods of record at Plateau Station and Sovietskaya are not long enough, however, to be conclusive. Some other low average annual temperatures are -67°F at Vostok during 1958 and 1959, and -59°F at Amundsen-Scott Station (90° S, elevation 9,186 feet) for the period 1957-1964 (2). During this same period at Amundsen-Scott, the July temperature averaged -74.5°F with the maxima averaging -69°F and the minima, -80°F (2).

(3) Temperature Ranges

Besides the most extreme absolute and average high and low temperatures, there are extreme differences between the highest and lowest temperatures that occur during a given period such as a year or 24 hours. Examples are the differences between summer and winter or day and night temperatures, which occur periodically and predictably and are usually greatest in interior or desert areas. Also, rapid changes can occur under certain weather conditions, e.g., foehns (warm, drying winds descending the lee sides of mountain ranges) and advection of cold air masses. Temperature falls resulting from the latter can be further intensified by loss of heat through radiation. Still other weather situations can cause extreme fluctuations in temperature.

U. S. greatest 2-minute temperature rise:
49 F°, from -4°F to 45°F,
Spearfish, S. Dak., 22 Jan 1943

Rapid City, S. Dak., had three temperature rises
and two falls of 40 F° or more during a period
of 3 hours and 10 minutes, 22 Jan 1943

Spearfish is located at 44°30' N, 104° W, elevation 3,637 feet, and Rapid City is at 44° N, 103° W, elevation 3,234 feet. They are in the Black Hills, a dome-shaped mass culminating in peaks over 7,200 feet above sea level, which slopes abruptly on the east and gradually on the west. This region lies mostly between 43° and 45° N, and 103° and 104°30' W; extreme temperature changes occur there rather frequently.

On 22 January 1943, very rapid and pronounced fluctuations in temperature took place in the Black Hills. The phenomenon, investigated by Hamann, was "essentially the result of the wavering motion of a pronounced quasi-stationary front separating Continental Arctic air from Maritime Polar air" (9). Also, local chinook* effects possibly contributed to the unusual conditions. At Spearfish, the temperature rose from -4°F to 45°F and

*A name given to foehns in the western United States.

returned to -4°F between 7:32 and 9:27 a.m. (9). During this period, in which there were many sharp variations, the record two-minute rise occurred. At Rapid City, the temperature rose from 5°F to 54°F between 9:20 and 9:40 a.m., fell to 11°F at 10:30 a.m., rose to 55°F at 10:45 a.m., fell to 10°F at 11:30 a.m., rose to 34°F at 11:50 a.m., fell to 16°F at 12:15 p.m. and rose to 56°F at 12:40 p.m. (9). Changes were so rapid that buildings were experiencing winter on one side and spring around the corner. The phenomenon also caused unusually high daily ranges in temperature, over 50 degrees at some places, and sharp contrasts between some nearby places. For example, at Lead, South Dakota, the temperature was 52°F, while at Deadwood, less than three miles away, it was -16°F (9).

b. Precipitation

Precipitation is measured by the depth to which it covers a horizontal unit area of the earth's surface during a given period. Precipitation is caught in gages whose diameter represents the horizontal unit area; the more representative the catch is of actual fall over the entire observation area, the more reliable the measurement is. For this reason, site, form, and exposure of the gage are important, and precautions need to be taken to prevent precipitation from splashing out of the gage or being blown out by wind. In hot, dry areas evaporation can be a problem. Various requirements to cover these points have been established by the World Meteorological Organization (23).

Gages are of two main kinds: the ordinary or non-recording gage, and recording gages. The former provide a means of collecting and measuring precipitation, and the latter incorporate mechanisms for recording the amount of fall during a given period or the rate of fall at any instant. Descriptions of the many varieties of recording and non-recording gages can be found in Middleton and Spilhaus, Meteorological Instruments (51), as well as in the WMO Guide (23).

Even with the most efficient instruments, functioning perfectly and in the most favorable sites and exposures, there are still problems in obtaining representative precipitation values. The standard gage diameter is eight inches in the United States. Thus the horizontal unit area covered by the measured precipitation is about 50 square inches, and between these areas there are often several miles; intense rainfall is often very localized and may be missed by the observation network. An example is described by Lautzenheiser and Fay (52). During a rainfall in August 1959, two gages in the town of Island Falls, Maine, neither in the official Weather Bureau network, each measured 6.35 inches. The next nearest gage measured 3.06 inches, and the nearest official network gages measured 0.59 and 0.25 inch, respectively.

(1) Greatest Precipitation

Generally, for precipitation to occur, moist air must be lifted and thereby cooled below its dew point. There are three major mechanisms by which air may be lifted: convective, cyclonic, and orographic. Lifting by different methods results in precipitation with different characteristics and geographical distributions, as well as different kinds of record extremes. Convective rain results from overturning of cooler air by warmer air from below and takes the form of heavy, localized showers, such as thundershowers. Convective showers tend to be most frequent in warm areas and seasons, and are responsible for many of the extreme short-period rainfalls.

Cyclonic precipitation results from mechanisms associated with low-pressure centers (cyclones) and with zones of convergence of different air masses (fronts). The most severe cyclonic storms, hurricanes or typhoons, bring very heavy and prolonged rain and are responsible for most of the extreme amounts that occur over a period of several hours or days. Certain parts of the world, mostly oceanic and coastal areas, lie along the tracks usually taken by these storms. The storms are prevalent in different areas at different times of the year; their tracks are mapped by month in the U. S. Navy's Marine Climatic Atlas of the World (52).

Orographic precipitation results from upward deflection of air when it strikes higher ground. This type often occurs in conjunction with convective and cyclonic types and tends to increase the amounts produced by them, the increase being greatest on steep slopes Also, precipitation can increase when sharply narrowing valleys between slopes act as funnels on up-valley winds. Highlands in the path of moisture-carrying winds from warm seas have abundant and frequent precipitation; such areas have the highest average annual rainfalls Among them are the east- and south-facing slopes of the Himalayas, the western slopes of the Andes in Colombia, and mountain ranges along the northwest coast of North America. Extreme average annual precipitation values often differ slightly in different sources, because of differences in the period of record. (This is also true of the extreme average values for other meteorological elements, of course.) The number of years on which the extreme precipitation averages included on the map are based are given, where known, in the list of extremes at the beginning of this report. Generally, a longer period of record would have more reliability than a short one.

World's greatest one-minute rainfall:
1.23 inches
Unionville, Md., 4 Jul 1956

The U. S. Weather Bureau's investigation of this record is described by H. H. Engelbrecht, State Climatologist for Maryland at the time it occurred, and G. N. Brancato (54). The extreme fall occurred during an afternoon of intense thunderstorms in the foothills of northern Virginia

and adjacent north-central Maryland. At Unionville, the total precipitation during the storm was 3.60 inches, of which 2.84 inches fell during a 50-minute period from 1450 to 1540 Eastern Standard Time. Rainfall was measured with a recording rain gage located in satisfactory exposure. Some 13 points pertaining to functioning of the gage were considered in evaluating this record by Engelbrecht, then State Climatologist for Maryland, and T. E. Hostrander, who was Substation Inspector. An enlarged photograph of the recording rain gage chart revealed that at chart time 3:23+ the pen was at 2.47 inches on the chart scale and at chart time 3:23- it was at 3.70 inches. It was concluded that "1.23 inches of precipitation occurred in an estimated period of one minute or less" (54). This exceeded the previous world record one-minute rainfall of 0.69 inch at Jefferson, Iowa, which, in turn, had exceeded the earlier record of 0.65 inch at Opid's Camp, California.

World's greatest 42-minute rainfall:
12 inches
Holt, Mo., 22 Jun 1947

G. A. Lott has examined the meteorological data available for this storm, and considered the factors responsible for its remarkable intensity (55). According to him, the storm occurred "as a local intensification in a long, narrow, warm sector convective system (the leading edge of which may be interpreted as an instability line) a short distance ahead of a surface cold front". He proposed a mechanism responsible for the local intensification, based on his analysis of the synoptic situation both at the surface and in the upper air.

World's greatest 12-hour rainfall:
53 inches on 28-29 Feb 1964
Belouve, La Réunion I.

World's greatest 24-hour rainfall:
74 inches on 15-16 Mar 1952 and

World's greatest five-day rainfall:
152 inches on 13-18 Mar 1952
Cilaos, La Réunion I.

La Réunion Island is located in the Indian Ocean at approximately 21° S, 55°30' E. It is about 30 by 40 miles in extent and very mountainous, with steep slopes and narrow valleys. Sea surface temperature is highest during the tropical cyclone season, reaching 81°F in March (10). The record-producing rainfall at Cilaos occurred during a tropical storm as did, presumably, that at Belouve and another very heavy rainfall (62.33 inches in one day and 136.83 in five days) at Aurere, in April 1958 (10). All three of these storms broke the previous 24-hour world record, 45.99 inches at Baguío in the Philippines in 1911, and the Cilaos storm broke the previous five-day world record of 150 inches at Cherrapunji, India, in August 1841.

The values given for Aurere and Cilaos were obtained from a survey of about six years of official published data for those places, and the February 1964 rainfall at Belouve was reported in a communication from the French Meteorological Service (10). Since these record-breaking amounts "were the result of an incomplete survey of a short period of record, there is a good chance that a more thorough survey of a longer period of record would disclose other, and perhaps even greater, amounts of similar magnitude" (10).

Northern Hemisphere's greatest 24-hour rainfall:
49 inches
Paishih, Taiwan 10-11 Sep 1963

Paishih is located at 24°33' N, 121°13' E at a 5,368-foot elevation on the island of Taiwan. Taiwan, like La Réunion, is very mountainous and is surrounded by warm ocean water, 82°F in August and September during the tropical storm season. The record rainfall, 49.13 inches, occurred during typhoon Gloria; and it was measured in a recording gage, thus adding to the reliability of the observation (10). Rain of similar intensity fell at nearby stations during the same storm. At one of these places, Paling, total rainfall during the typhoon was greater than that of Paishih, and for some durations, intensity might have been greater. However, no further information on Paling is available.

Dharampuri, India, had a 24-hour rainfall of
39 inches
2 Jul 1941--possibly the world's greatest on flat terrain

Information on this rainfall extreme was obtained in 1962 by the late Paul Siple, then Scientific Advisor to the Director of Army Research (12). Dr. Siple obtained it from the Director of the Indian Central Meteorological Research Institute of Poona, India. Dharampuri is at latitude 20.5° N in the Surat District of the Gujarat States According to Siple,

> "Institute personnel believe this to be a maximum rain on essentially flat terrain. Actually, it was a monsoon rain, and the Western Ghats (mountains) must have had some effect. However, the Poona meteorologists minimized the orographic influence, for the location of the rainfall was not in the immediate vicinity of high mountains."

Australia's greatest 24-hour rainfall:
36 inches
Crohamhurst, Queensland 3 Feb 1893

This record, discussed by Newman, is officially accepted and, apparently, quite reliable (13). It occurred during a cyclonic storm in which comparable heavy rain fell at nearby stations.

World's greatest average annual precipitation:
460 inches
Mt. Waialeale, Kauai, Hawaii

According to the most recent official sources, "normal annual precipitation at Mt. Waialeale is 460 inches, the highest recorded annual average in the world" (14). This amount is based on data for the period from 1931 through 1960. An average of 472 inches has been quoted in other sources, based on data for 1912 through 1949 (15). Mt. Waialeale also had the greatest precipitation for one year of any place in the United States, 624 inches between 24 July 1947 and 27 July 1948 (11). This mountain, which is located at 22°04' N, 159°30' W, is 5,170 feet high. Environmental conditions pertinent to the record rainfall are described by Henning (56). According to him, elevation of the storage rain gage is 1,547 meters (5,075.5 feet), and measurements are made at three-month intervals. He found that precipitation in the area diminished rapidly with height and suggests the existence of a "daily course of rainfall" due to the higher elevation of parts of the island.

South America's greatest average annual rainfall:
354 inches
Quibdó, Colombia

Quibdó is situated at an elevation of 120 feet at 5°41' N, 76°40' W. A rainfall average of 413 inches at Quibdó, based on data from 1931 through 1946 taken from Colombian sources (59, 60), was cited on the 1964 revision of the Weather Extremes map. Earlier maps cited a value of 342 inches at Buena Vista, Colombia (15). The value of 354 inches, shown on the current revision, was obtained by correspondence with Environmental Data Service (6).

Alaska's greatest average annual precipitation:
220 inches
Little Port Walter

Little Port Walter is located at 56°23' N, 134°39' W in southeastern Alaska where coastal ranges and moisture-laden air from the Gulf of Alaska combine to produce abundant precipitation. Many places there have annual averages over 100 inches (57). According to official sources, Little Port Walter has the greatest recorded annual average precipitation in Alaska (52). This station, located near the southern end of Baranof Island, also had the greatest precipitation in Alaska during a single calendar year, 269.30 inches in 1943 (11). In the conterminous United States, the highest average annual precipitation, 144.43 inches, is found at Wynoochee on the southwestern slope of the Olympic Mountains in Washington (6), and the greatest amount during a calendar year, 184.56 inches, occurred in this locality at Wynoochee Oxbow in 1931 (11).

(2) Least Precipitation

Generally, aridity occurs where moisture and air-lifting mechanisms are scarce, e.g., in continental interiors, on lee sides of high mountains, on coasts adjacent to cool currents, in zones of higher atmospheric pressure where the air is subsiding, and in high latitudes. Some places where these conditions are found are in North Africa and adjacent southwest Asia between 15° and 35° N; western South America between 5° and 30° S; eastern South America between 35° and 50° S; western Africa between 15° and 35° S; western and interior Australia; interior Asia; and parts of western North America between 25° and 40° N.

As with records of high average precipitation, those of low average precipitation vary according to the years on which they are based, and tend to be more reliable for a longer period. In some very dry areas, several years can pass without any precipitation at all. There is some uncertainty about the longest number of years without rain that was ever officially recorded. A rainless period of 14 years at Iquique, Chile, seems to be generally accepted (11), and a 20-year average of 0.00 inches at Assuan, Sudan was noted (4) but not verified.

Africa's lowest average annual precipitation:
$<$ 0.1 inch during a 39-year period
Wadi Halfa, Sudan

Wadi Halfa is located at an elevation of 412 feet, at 21°55' N, 31°19' E. In previous Weather Extremes maps, a record was cited of 19 years without rain there. This record was obtained from a photostat of a U. S. Weather Bureau Index of Climatic Data, which cited an official British publication (61) as its source. The particular years of observation are not given, nor is information on whether it rained during the 20th year or whether the observations just happened to stop after 19 years.

(3) Precipitation Variability

Variations in precipitation can be upward, i. e., occurrence of above-average amounts, or downward, i. e., occurrence of below-average amounts or even drought. Among the factors causing them are displacements of ocean currents and differences in strength of the monsoonal circulation from year to year. Coasts adjacent to cold currents are generally dry, but if the current deviates, even slightly, making room for warmer water, relatively abundant rainfall can occur, as in the coastal areas of Chile and Peru. Disastrous droughts in northeast Brazil might be due to the opposite effect, invasion of warmer water by cold currents. The other factor, differences in strength of monsoonal circulations, is most pronounced along the borders of areas covered by these seasonal winds. During years of weak monsoon, less territory is covered by the rain-bearing winds and less rain is deposited by them.

Debundscha, Cameroon, has
75 inches
average annual variability of precipitation

Absolute average variability and relative variability of precipitation at 384 places throughout the world were tabulated by E. Biel (16) and examined statistically by V. Conrad (62). Places with highest absolute average variability (difference between mean value and individual yearly value averaged for a given number of years) are Debundscha, Cameroon, and Cherrapunji, India, with 75.28 and 66.02 inches, respectively. Debundscha is located at 4°01' N, 9°01' E, at 16 feet elevation, and has the greatest average annual precipitation in Africa, 405 inches (3). Cherrapunji is located at 25°02' N, 91°08' E, elevation 4,311 feet, and has the greatest average annual precipitation in Asia, 450 inches (3). Because the averages at these places are so high, the differences from year to year can be correspondingly high without being extreme in proportion to the mean. The greatest absolute variability (i.e., the greatest difference between the amounts of precipitation recorded during the highest and lowest years) might have occurred at Cherrapunji, India. At this place, which holds several rainfall records for periods of 15 days and over, the greatest precipitation during a calendar year was 905.1 inches and the least was 282.6, a difference of over 600 inches

Malden Island, Line Islands, has a
71 percent
average annual relative variability of precipitation

Places with the greatest relative variabilities are Malden Island in the Line Islands and Aden in the southwestern corner of the Arabian peninsula, with 71 and 66 percent, respectively (16). Malden Island is located at 4°03' S, 155°01' E, at an elevation of 20 feet. Its average annual precipitation is 28.6 inches, and its absolute average variability is 20.24 inches. This great relative variation is thought to be due to displacements of ocean currents. Aden is located at 12°08' N, 45° E, elevation 95 feet. Its average annual precipitation is 1.9 inches, and the absolute average variability, due to variations in monsoonal circulation, is 1.22 inches. Other desert stations such as Arica and Iquique, Chile, which sometimes have no rain at all for several years, also have very high relative variabilities.

Lhasa, Tibet, had a
108 percent
average annual relative variability
of precipitation, 1935-1938

Lhasa is located on the Tibetan plateau at 29°40' N, 91°07' E, elevation 12,090 feet. It is in an approximately east-west valley flanked on both sides by mountains of 15,000 to 16,000 feet. Its climate has

been described by Ginn-Tze Hsü, who established a meteorological station there in 1934 (63), and also by A. Lu (17) and H. Flohn (64). In 1936, the annual precipitation reported for Lhasa, 198.3 inches, was more than 10 times greater than the average amount. Data for the years 1935 through 1938 from Lu's paper (17) were calculated by Conrad's methods (62) to obtain the absolute average variability of 67.7 inches and a relative variability of 108 percent.

Though calculated by the same method, the values of relative variability for Malden Island and for Lhasa are not really comparable because the former incorporated data for "many years" (62), and the latter for only the four years that were immediately available. Over a long-term period, Lhasa's relative variability might or might not exceed Malden Island's; by the same token, Malden Island may never have experienced such an extreme fluctuation. This might be an interesting topic for investigation.

There is also some doubt as to the authenticity of the amount of precipitation recorded for 1936. According to Lu (17) and Hsü (63), the remarkable amount was the effect of invasion by the southwest monsoon. This monsoon, which obtains its moisture mostly from the Indian Ocean, varies greatly in strength from year to year. Normally, it climbs over the Himalaya Mountains from the south but brings only a limited amount of precipitation to Lhasa. Sometimes it is too weak to cross the mountains; occasionally, however, it is strong enough to surge into southern Tibet with heavy downpours.

Flohn considers the 1936 value to be questionable and attributes it to a possible misplacement of a decimal point by a partly educated weather observer (64). On the basis of Lu's data and data for most of the years from 1941 to 1955, Flohn found no amounts that even approached that of 1936. The highest was 22.9 inches, and the average was 17.2 inches if the 1936 value was not included, 27.1 inches if it was. The lowest amount was 9 inches. The frequency of precipitation, as indicated by the number of rainy days during 1936, was not unusual. There were 87 days with more than 0.1 mm (approx. 0.004 inch) precipitation in 1936, 89 in 1935, 87 in 1937, and 93 in 1938 (18). Furthermore, Gyantse, in the same climatic region as Lhasa at 28°56' N, 89°36' E, elevation 10,486 feet, had no similar extreme fluctuation in a 38-year period. In 1936 Gyantse had 13 inches more than the average precipitation, but in six other years it had amounts that exceeded the average by more than this.

However, Hsü was at Lhasa in 1936, presumably as the station observer or supervisor, and he writes about the unusually heavy rain and its causes (63) and informed Lu (17) of the difference between the rainfall in 1936 and in other years. Normally, rainfall at Lhasa comes from thundershowers, but in 1936, only 23 percent was of this type and 69 percent was from

night-time rain, caused possibly by interaction between the monsoon and cold air masses from the north (17). In another paper, Lu described a similar extreme rainfall fluctuation at Omei Shan, China, to the east of Lhasa, at approximately 29°30' N, 103°30' E, elevation 10,023 feet (65). The annual mean there is 73 inches, but during the Second Polar Year from August 1932 to August 1933 it had 319 inches, "the largest amount ever recorded in China in a 13-month period" (65). This difference of 246 inches between the annual mean and the 1932-33 value is even greater than th 145-inch difference between Lhasa's annual mean and its 1936 precipit. n. Flohn's paper also mentioned Omei Shan, but his figures differ somewhat from Lu's, with a 25-inch annual mean and 300 inches in 1932-33, making a difference of 275 inches (64).

(4) Hail

Largest officially recorded hailstone:
1-1/2 pounds
Potter, Neb. 6 Jul 1928

Unofficial claims have been made of larger stones. Some interesting references have been found on hail in India (66, 67). In one case, stones over two pounds in weight were said to have fallen (66); in another (67), hailstones five inches or more in diameter reportedly wiped out a village!

(5) Snow

There are two main ways of measuring snowfall depth: by direct measurement of fresh snow on open ground with a graduated ruler or scale, and by a snow gage. Precautions need to be taken against drifting or blowing snow, or, if the open ground method is used, against measurement of old snow. When there are strong winds, the snow gage is more accurate. Greatest amounts of snowfall--as of rainfall--occur in areas where there is moist air and a mechanism for lifting it. They tend to occur more commonly in the middle latitudes rather than at the very high latitudes where there is less moisture. For instance, the greatest North American snowfall depths for 24 hours, one storm, and during a season occurred in the conterminous United States rather than in Canada or Alaska.

North America's greatest 24-hour snowfall
76 inches
Silver Lake, Colo. 14-15 Apr 1921

Silver Lake is located at approximately 40° N, 105°40' W, at 10,220 feet elevation in the Colorado Rockies. The snowfall there in April 1921 established several records: 76 inches in 24 hours, prorated from a measured fall of 87 inches in 27-1/2 hours, 95 inches in 32-1/2 hours, 98 inches in 72 hours, and 100 inches in 85 hours (68). According to Paulhus, the measurement was examined thoroughly before being accepted by

the U. S. Weather Bureau (68). "There was no evidence to indicate that the measurement was any less reliable than that of other heavy snowfalls, and it appears that a snowfall of this magnitude is meteorologically possible". The maximum amount of snow that can fall in 24 hours has been estimated as approximately 72 inches for snow with a density of 0.10 under normal packing conditions, and correspondingly greater for lesser density (69). The density of the snow at Silver Lake was 0.06 (68). During the storm, thunder occurred in various parts of the region, indicating widespread convective activity, and the combined convective and orographic influences produced excessive amounts of snow at several places. In addition to the record at Silver Lake, a fall of 62 inches in 22 hours was reported at Fry's Ranch, Colorado; both of these exceeded the previous United States record of 60 inches in 24 hours at Giant Forest, California, in January 1933 (68).

c. Other Extremes

Besides temperature and precipitation, several other meteorological and climatic conditions are shown on the map. For each of these, the most extreme conditions have their own particular set of causes, limits, and distributions in time and space, and for each there are problems in obtaining accurate measurements. In evaluating reliability of records of extreme occurrence of these conditions, all of these factors should be taken into consideration.

(1) Thunderstorms

Thunderstorms are most prevalent in warm weather and, in some places, during the rainy season. However, although thunderstorms frequently produce heavy rainfall, there are places where seasons of rainfall and thunderstorm maxima do not coincide. Some very rainy places have few thunderstorms, while places with very frequent thunderstorms can have relatively small amounts of rainfall (70).

Kampala, Uganda has
242 average annual thunderstorm days

Bogor, Indonesia, averaged
322 thunderstorm days per year
1916-1919

Kampala is located at 0°20' N, 32°36' E at a 4,304-foot elevation. It has the highest number of thunderstorm days of any place listed in the World Distribution of Thunderstorm Days (18). However, statistical curves indicate "that the absolute occurring maximum is somewhat higher, approximately 250 or 260 thunderstorm days annually, although such a location has not as yet been found" (70). The record for Kampala is based on a period of 10 years, but the particular years are not given. Then too,

ten years might not be long enough to prove that Kampala holds the world's record. Thunderstorm frequency can change radically over a long-term period, as is evidenced by Bogor, Indonesia (6°30' S, 106°48' E). The mean annual number of thunderstorm days there changed from 151 in the years 1841-1857 to 322 in 1916-1919; it ranged from 4 to 41 for the years 1953 through 1962 (19). Cuiabá, Brazil (15°35' S, 56°06' W) is cited as a place where the frequency has remained high (slightly above 100 days a year) for a long period, 1911-1959 (19). Perhaps, comparison of the environmental conditions at Kampala, Cuiabá, and Bogor would be of interest.

(2) Air Pressure

The pressure value for a given unit area of surface very nearly represents the actual weight of a vertical column of air of the same unit area extending upward from that surface to the top of the atmosphere. At sea level, this column of air averages about 14.7 pounds (29.92 inches of mercury) per square inch of exposed surface, but the weight varies with latitude and with changes in daily weather. It falls with altitude from an average of 31.3 inches in the earth's deepest depression, 1,300 feet below sea level, to less than half that amount (about 14.9 inches) at 18,000 feet. At the top of the world's highest mountain, 29,028-foot Mt. Everest, it would be about 9 inches.

Air pressure is usually measured by mercurial or aneroid barometers. The former balances pressure of the atmosphere against the weight of a column of mercury. The aneroid or elastic type contains a hollow metal chamber, partly emptied of air and sealed, which expands and contracts as the pressure changes. Mercurial barometers are generally more accurate, but the aneroids are smaller and more portable. Since mercury is affected by temperature and gravity, adjustments must be made in the readings of mercurial barometers to allow for these factors. Also, in order to standardize readings of any kind of barometer when made at different times and places, adjustments are required to compensate for errors in the individual instrument used (index error) and for differences in altitude. For the altitude correction the station pressure readings are usually equated to sea level pressure, and these are the values which are recorded. There are possible sources of error peculiar to each type of instrument, as well as from the various types of adjustments. For example, different values can be obtained when different methods are used for reducing the actual or station pressure to its sea level equivalent.

The highest station pressures occur at the lowest elevations, i.e., in depressions below sea level such as Death Valley, California, where the lowest point is -280 feet; the Qattara depression in northwestern Egypt, with a minimum elevation of -436 feet; and the shores of the Dead Sea between Israel and Jordan, at -1,286 feet. In the Dead Sea area, a station pressure of 31.91 inches was reported at Sedom (the biblical Sodom) on 21 February 1961 (71). Another depression, the Turfan in central Asia at approximately

45° N, 90° E, is thought to have station pressures similar to or even higher than those of the Dead Sea area (72). However, after the adjustment to sea level is made for pressure readings below sea level, the values are lower.

At or near sea level, high pressures occur along Arctic coasts. Values of 31.37 inches (31.38 sea level equivalent) and of 31.40 inches (31.41 sea level) have been recorded at Clyde in northeastern Canada and at Myggbukta in East Greenland on 18 January 1958 and 15 January 1940, respectively (71, 73). At stations above sea level the pressure readings are lower, but when equated to their sea level equivalents, the values recorded are higher. Of these, the highest occur in Siberia during winter. In addition to the world record of 31.84 inches shown on the map for Barnaul and the previous world record of 31.75 inches at Irkutsk on 14 January 1893, a new and higher value of 31.97 inches was reported from Agata Lake, Siberia, at 66°53' N, 93°28' E, altitude 863 feet, on 31 December 1968 (72). This value was corroborated by widespread high pressures on that day, including a barometer reading of 31.71 inches at Igarka, at 67°30' N, 86°35' E, elevation about 100 feet (72).

World's highest sea level air pressure:
31.84 inches
Barnaul, Siberia, 23 Jan 1900

Barnaul is at 53°20' N, 83°48' E, altitude 558 feet. The Barnaul record has been discussed by Woeikof (74) and by Hann (75) According to Woeikof, the maximum pressure observed was 789.2 mm Hg (30.89 inches), which reduced to sea level is 808.7 mm Hg (31.86 inches). According to Hann, this reduction to sea level was based on the outdoor temperature, -38°C (-36°F), at the time the observation was made; but if the mean monthly temperature of January 1900, -28°C (-33°F) were used for the reduction, the result would be 808.3 mm Hg (31.847 inches). The latter is preferable because due to the prevalence of temperature inversions, use of the actual temperature "gives spuriously high pressures" (72).

The lowest station pressures occur at the highest altitudes, e.g., in the Himalayas of Asia, the Andes in South America, and the Rockies in western North America. Beginning at about 4,000 feet, the average station pressures are lower than the most extreme that occur at sea level. At the approximate upper limit of weather stations, 15,000 feet, standard pressure is 16.90 inches and the extreme lowest is estimated at about 14.76 inches (48). The most extreme low sea level pressures, and the most rapid falls in pressure, occur during hurricanes and tornadoes. During the latter, it is estimated that the drop in pressure can be "as great as one fifth of an atmosphere", i.e., about 6 inches (76). Another estimate is for "a reduction of no more than one-fourth of the pre-existing pressure", which could occur "within 15 seconds" (48).

World's lowest air pressure at sea level
(excluding tornadoes):
25.90 inches
estimated by aerial reconnaissance in eye of Typhoon Ida at
19° N, 135° E. 24 Sep 1958

Reliability of the estimated record has been evaluated by Jordan (77). It was based on a dropsonde observation made from the 700-mb level by a U. S. Air Force reconnaissance aircraft of the 54th Weather Reconnaissance Squadron, about 600 miles northwest of Guam. In the observation, the 700-mb height was determined from the pressure and radio altimeters aboard the aircraft, and the 850-mb height and sea level pressure were computed from temperature and humidity data measured by the aircraft instruments at flight level and by the dropsonde instrument at levels below the aircraft. According to Jordan, the sounding was found to be hydrostatically consistent and the vertical temperature distribution was realistic (77). A source of major error in this type of measurement would be in the aircraft altimetry; but, on reconnaissance aircraft, calibration checks are a routine part of each flight. Dropsonde observations from two other aircraft, made about eight hours earlier and 23 hours later, respectively, both reported sea level pressures lower than the previously accepted lowest pressure of 26.185 inches from the SS Sapoerea. Lower values than the Sapoerea's were also reported in 1953 during Typhoon Nina, with dropsonde sea level pressures of 886 mb (26.17 inches) and 883 mb (26.04 inches) (77). However, the record taken on the Sapoerea, 460 miles east of Luzon, Philippine Islands, on 18 August 1927 was an actual measurement rather than an estimate, and still remains the lowest measured pressure at sea level (11).

(3) Solar Radiation

Measurements of the flux of solar radiation penetrating to the lower layers of the atmosphere can be subdivided into several main classes. Values considered here are for global solar radiation received on a horizontal surface. "This includes both radiation received direct from the solid angle of the sun's disc and also radiation that has been scattered or diffusely reflected in traversing the atmosphere" (23). Such measurements are usually made with pyranometers, and, as in all radiation measurements, considerable care and attention to detail is required to insure accuracy. Several points to be evaluated in estimating accuracy of radiation measurements are listed in the WMO Guide (23).

The world's highest daily amounts of solar radiation are received on the Antarctic Plateau during summer when there are 24 hours of continuous daylight (78). The North Polar area also has continuous daylight during its summer, but at that time of the year the earth is about three million miles further from the sun. Consequently, about seven percent more solar radiation impinges on the top of the Antarctic's atmosphere than on the Arctic's during mid-summer (78). The highest theoretical hourly solar

radiation value is 117 langleys per hour (based on the solar constant of 1.95 langleys per minute). Values have been reported of 113 langleys per hour at Malange, Angola (9°33' S, 16°22' E, altitude 3,710 feet) on 7 November 1961 and of 112 langleys at Windhoek, South West Africa (22°34' S, 17° 06' E, altitude 5,646 feet) on 20 December 1956 (79, 80).

South Pole has
955 langleys
average daily insolation in December

This record was obtained by averaging daily values of hemispheric global solar radiation, which were available from Amundsen-Scott Station for the Decembers 1958 through 1965 (22). The resultant value was 954.6 langleys. Amundsen-Scott is located at an elevation of 9,186 feet, at 90° S. However, the average daily insolation could be greater at other stations in the Antarctic.*

(4) <u>Wind Speed</u>

Of all the elements, wind is most variable. To compare wind speeds reported from various places and times, information should be known about the height and exposure of the measuring instrument (anemometer), the type of instrument and record, and the time interval covered by the measurement. Wind speed is usually measured by either rotating or pressure anemometers. In the former type, wind passage is measured by the rate of motion imparted to a freely-rotating mechanism, and a timing mechanism is usually combined with the anemometer to indicate the rate of passage. Pressure anemometers measure the instantaneous speeds (actually averages for about one second) by means of pressure effects, i.e., force applied to a surface or surfaces. The time intervals of wind observations differ between countries and even between stations. In the United States, the extreme values tabulated are: the greatest average speed over a 5-minute interval, <u>maximum speed</u>; the speed of the fastest mile of wind from the record of rotating anemometers, <u>extreme speed</u>; and the highest reading of the instantaneous recording anemometers, <u>strongest gust</u> (81). In addition, extreme average values are obtained from records of the total wind passage in each hour from recording rotation anemometers at the principal weather stations (81).

Winds are strongest at the times and places of maximum temperature and pressure gradients. They increase with altitude and during thunderstorms, hurricanes, and tornadoes. Gusts are sudden brief increases in the speed of the wind, usually less than 20 seconds in duration (32), and are known

*Personal communication, P. Dalrymple and M. Kuhn, Regional Environments Division, Earth Sciences Laboratory, US Army Natick Laboratories.

to exceed 200 miles per hour in hurricanes (82). A tornado is defined as "a slightly funnel-shaped, upward-spiraling wind column of destructive velocity" (82). It has been estimated that horizontal velocities of tornadoes increase rapidly toward the center from about 40 to 50 miles per hour around the edges to 200 to 500 miles per hour or more near the center (82). Geographic areas subject to tornadoes or hurricanes would have the most extreme high winds, while areas "in the paths of the storms of middle latitudes" (81) would have the highest average wind speeds.

World's highest surface wind
(excluding tornadoes):
231 miles per hour, peak gust, and
188 miles per hour, five-minute wind speed, on
12 Apr 1934 and

U.S. highest average annual wind speed:
35 miles per hour (35.4)
Mt. Washington, N.H.

Winds are stronger at the summit of this 6,288-foot mountain, at 44° 16' N, 71°18' W, than they are at the same elevation in the free air some distance away. "This is probably due to 'uplift' over the slope or to the Bernoulli effect introduced by the surrounding mountains. Windspeeds of 100 mph are not uncommon" (21). The speed of the peak gust was measured by a heated rotation anemometer, but, in such strong winds, no apparatus can record the air-flow except approximately, and actual velocity may be in error by 10 to 40 miles per hour (83, 84). The 231 miles per hour value is documented in the official records (21) and accepted by the Environmental Data Service (6). A value of 225 miles per hour, after anemometer calibration, is given in some sources (81) and was cited in previous editions of the map. Direction of the wind during the gust was from the southeast, the direction from which the most severe storms in the Mt. Washington area usually come. Its force, due to the reduced air density on the mountain top, was equal to that of about a 180-mile-per-hour wind at sea level (81).

The highest 5-minute maximum speed at Mt. Washington is 188 miles per hour, recorded on the same day as the peak gust (11). The second highest gust that occurred on this mountain is apparently the 189 miles per hour estimated during the hurricane of 21 September 1938 (83). The strongest speed that was actually measured during the 1938 hurricane was 183 miles per hour (corrected) at the Blue Hill Observatory in Milton, Massachusetts (81). The average annual wind speed recorded on the mountain varies with the period of observation. The value of 35.4 miles per hour was taken from the most recent available official source (6), but figures of 36.9, 37.2, and 34.4 were also found (15, 84, 85).

(5) Dew Point (Humidity)

Dew point is "the temperature to which a given parcel of air must be cooled at constant pressure and constant watervapor content in order for saturation to occur" (32). This temperature is measured by instruments in which a mirror or other element is cooled to the saturation point. High dew points indicate high humidity, and low dew points, low humidity. As far as could be ascertained, there are no accepted records of most extreme high or low dew points. The high values cannot be higher than the temperature of the body of water from which the vapor originates. They occur in proximity to water bodies with high surface temperatures such as parts of the Gulf of California, the Red Sea, the Persian Gulf, and, possibly in some tropical swamplands. A maximum value of 96.8°F has been reported from Khanpur, Pakistan (28°39' N, 70°41' E)*. "The lowest dewpoints correspond to the lowest temperature at or just above the tropopause, which may be as low as -130°F in the tropics and possibly -150°F in polar regions" (48, 87).

Assab, Ethiopia, has
84°F
Average afternoon dew point in June

The dew point value for Assab was taken from a footnote in a report by A. Dodd (22): "Recently available data furnished by the National Weather Records Center indicate that very high dew points occur also in the Red Sea littoral. Assab and nearby Ras Andahglie on the Red Sea coast of Eritrea (Ethiopia) had average afternoon dew points higher than 84°F." These might not be the world's highest average dew points, but they are included on the map to indicate the limits that can be reached.

(6) Fog

U. S. foggiest place:
2552 hours per year average
Cape Disappointment, Washington

Eastern U. S. foggiest place:
1580 hours per year average
Moose Peak, Maine

These records were obtained from M. A. Arkin, Chief, Foreign Branch of the Environmental Data Service, Environmental Science Services Administration of the U. S. Department of Commerce. They are based on fog signal operation and on low visibility operation of radio beacons at light

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*Unverified data from Air Force Cambridge Research Laboratory, Bedford, Mass.

stations, lightships, and other Coast Guard units during a period of 10 years or longer. Also, for a 4-year period at Willapa, Washington, the average was 3,863 hours per year, and for one of those years the total was 7,613 hours.

4. Conclusions

From the foregoing examples and discussions, several points seem to stand out:

(1) For each meteorological and climatological element, there are certain conditions or combinations of conditions that favor extreme values and are most likely to occur within particular geographical areas or seasons of the year; there are upper and lower limits of possibility of occurrence of each element. The records shown on Figures 1 and 2 appear to be within the limits of possibility and to have occurred in places and at times in which the necessary conditions could be expected. However, other occurrences of equal or greater extremity could have happened at other places in the same areas or at other times in the same places without being recorded or without being publicized. There is no routine exchange of such information between different countries.

(2) For each meteorological and climatological element, there are factors of site, instrumentation, and observational procedure which can affect the measured values. To insure uniformity of measurements, certain standardized equipment and procedures are recommended by the World Meteorological Organization. However, standardized equipment can malfunction and errors can be made in observation and recording, even under standard procedures. Further, improvements in the reliability of measurements continue to be made as knowledge of both technology and the physical environment increases. Some of the earlier records might have different values if measured with the newest instruments and procedures; even now, extremes are sometimes not measured exactly, or at all, because they exceed the scale of standard meteorological instruments or their rate of response (48). For these reasons, it is not to be assumed that any one of the values shown on the maps in this report is correct to the tenth of a decimal place, but those for which a claim of being most extreme is made have sufficiently passed inspection to be accepted by appropriate meteorological agencies.

(3) Considerable research remains to be done both on the general subject of extreme weather and climate and on the records of individual extremes. There is more to be known about the causes of extreme conditions as well as their absolute limits, frequencies, and distributions in time and place. Further search would probably yield additional world and local records of extremes which are not included on the present maps. As the "state-of-the-art" improves, records of other kinds of weather phenomena might be included: e.g., large raindrops, prolonged durations of rain,

and highest concentrations of aerosols in the air or of various chemicals in rain water. Other maps might indicate extreme phenomena of the upper air, of the sea, or of land topography (highest mountains, deepest valleys, etc.).

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13. ABSTRACT

This report consists of a map of world and continental weather extremes and a map of North American weather extremes, with comments on the reliability of the records shown Included are highest and lowest temperatures, largest temperature ranges, greatest and least amounts of precipitation for various durations, maximum precipitation variability, greatest thunderstorm frequency, highest and lowest atmospheric pressure, highest solar radiation, largest hailstones, greatest snowfall, highest wind speed, highest humidity, and most frequent occurrence of dense fog. Both the absolute extreme and the most extreme annual average are given for most of the elements. As far as possible, the records are taken from official sources, and all of them are documented. Conditions of site, instrumentation, observational procedure, and other factors pertinent to the reliability of extremes are discussed.

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Weather	9,8					
Weather observations	8					
Meteorological charts	0					
Temperature	9					
Precipitation (meteorology)	9					
Atmospheric pressure	9					
Solar radiation	9					
Wind (meteorology)	9					
Weather intelligence	4					
Humidity	9					
Fog	9					